Global and Planetary Change 75 (2011) 76–82

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Terrestrial waters and sea level variations on interannual time scale

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ARTICLE INFO

Article history:
Received 25 May 2010
Accepted 18 October 2010
Available online 26 October 2010

Keywords:
land water storage
sea level variations
tide gauges
satellite altimetry

ABSTRACT

On decadal to multidecadal time scales, thermal expansion of sea waters and land ice loss are the main contributors to sea level variations. However, modification of the terrestrial water cycle due to climate variability and direct anthropogenic forcing may also affect sea level. For the past decades, variations in land water storage and corresponding effects on sea level cannot be directly estimated from observations because these are almost unexistent at global continental scale. However, global hydrological models developed for atmospheric and climatic studies can be used for estimating total water storage. For the recent years (since mid-2002), terrestrial water storage change can be directly estimated from observations of the GRACE space gravimetry mission. In this study, we analyse the interannual variability of total land water storage, and investigate its contribution to mean sea level variability at interannual time scale. We consider three different periods that, each, depend on data availability: (1) GRACE era (2003–2009), (2) 1993–2003 and (3) 1955–1995. For the GRACE era (period 1), change in land water storage is estimated using different GRACE products over the 33 largest river basins worldwide. For periods 2 and 3, we use outputs from the ISBA-TRIP (Interactions between Soil, Biosphere, and Atmosphere—Total Runoff Integrating Pathways) global hydrological model. For each time span, we compare change in land water storage (expressed in sea level equivalent) to observed mean sea level, either from satellite altimetry (periods 1 and 2) or tide gauge records (period 3). For each data set and each time span, a trend has been removed as we focus on the interannual variability. We show that whatever the period considered, interannual variability of the mean sea level is essentially explained by interannual fluctuations in land water storage, with the largest contributions arising from tropical river basins.

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1. Introduction

On decadal to multidecadal time scales, thermal expansion of sea waters and land ice loss are the main contributors to sea level variations (Bindoff et al., 2007). However, modification of the terrestrial water cycle due to climate variability and direct anthropogenic forcing may also affect sea level (Milly et al., 2010). While in recent years, thermal expansion and land ice melt were the object of numerous investigations (Bindoff et al., 2007; see also Cazenave and Llovel, 2010 for a review), the terrestrial water contribution to sea level has been less studied (Milly et al., 2010). For the past decades, variations in land water storage caused by climate change and variability cannot be directly estimated from observations because these are almost unexistent at global continental scale. However, global hydrological models (or land surface models) developed for atmospheric and climatic studies can be used for estimating total water storage (Milly et al., 2010). The models compute the mass and energy balance at the Earth surface, as well as water storage change in soil in response to prescribed variations of near-surface atmospheric data (precipitation, temperature, humidity and wind) and radiation. Using atmospheric re-analyses and the Orchidee land surface model outputs, Ngo-Duc et al. (2005a) estimated the terrestrial water storage contribution to sea level over 1950–2000. They found no climatic long-term trend but large interannual/decadal fluctuations, of several millimetre amplitudes when translated into sea level equivalent. A similar result was also found by Milly et al. (2003) using the Land Dynamics model over 1980–2000. Direct human intervention on land water storage and induced sea level changes have been estimated in several studies (e.g., Chao, 1995; Sahagian, 2000; Gornitz, 2001; Chao et al., 2008). The largest contributions come from groundwater pumping (either for agriculture, industrial and domestic use) and reservoir filling. Surface water depletion has a non

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doi:10.1016/j.gloplacha.2010.10.008

negligible contribution. Although detailed information is lacking, and estimates vary significantly between authors, ground water depletion may have contributed to past decades sea level rise by 0.55–0.64 mm/yr (e.g., Gornitz, 2001). A recent update by Wada et al. (2010) suggests an even larger contribution of groundwater depletion, of 0.8 ± 0.1 mm/yr sea level rise over 1960–2000. During the past 50 years, several tens of thousands of dams have been constructed over world rivers, leading to water impoundment into artificial reservoirs, hence negative contribution to sea level. Several attempts have been made to estimate the total volume of water stored in artificial reservoirs over the past half century (e.g., Chao, 1995; Vörösmarty et al., 1997; Sahagian, 2000; Gornitz, 2001). Chao et al. (2008) reconstructed water impoundment history of nearly 30,000 reservoirs constructed during the 20th century and estimated a −0.55 mm/yr contribution to sea level due to dams and artificial reservoirs during the past half century. Hence, for the last few decades, effects on sea level from groundwater depletion and water impoundment behind dams are of the same order of magnitude and opposite sign. However, a slight positive residual contribution to sea level, of ~0.25 mm/yr, may be expected if the groundwater depletion component dominates.

For the recent years, terrestrial water storage (TWS) change can also be estimated from observations of the GRACE space gravimetry mission. The GRACE mission, launched in 2002, was developed by US National Aeronautics and Space Administration (NASA) and the German Aerospace Centre (DLR), to measure spatio-temporal change of the Earth gravity field at a monthly interval (Tapley et al., 2004). On time scales ranging from months to decades, these temporal gravity variations mainly result from surface redistribution of water inside and among the outer fluid envelopes of the Earth (Wahr et al., 2004). Thus, on land, GRACE provides measurements of TWS change in river basins. Two recent studies (Ramillien et al., 2008; Llovel et al., 2010a) have estimated the water volume trend in the ~30 largest river basins worldwide using GRACE, and found small net water volume change globally since 2003, with a ±0.2 mm/yr sea level rise contribution.

In the present study, we focus on the interannual variability of TWS rather than on the trend, and investigate its contribution to mean sea level variability. We consider three different periods which each depends on data availability: (1) 2003–2009 (GRACE era), (2) 1993–2003 and (3) 1955–1995. For the GRACE era (period 1), accordingly, we use GRACE data to estimate TWS. For periods 2 and 3, we estimate TWS variations from outputs of the ISBA-TRIP (Interactions between Soil, Biosphere, and Atmosphere—Total Runoff Integrating Pathways) global hydrological model (Alkama et al., 2010). For sea level, we used tide gauge-based values for period 3 and satellite altimetry for periods 1 and 2 (see Section 3).

2. Effect of land water storage change on sea level

Excluding ice sheets and glaciers, fresh water on land is stored in various reservoirs: snow pack, rivers, lakes, man-made reservoirs, wetlands and inundated areas, root zone (upper few meters of the soil) and aquifers (groundwater reservoirs). Terrestrial waters are continuously exchanged with atmosphere and oceans through vertical and horizontal mass fluxes (precipitation, evaporation, transpiration of the vegetation, surface runoff and underground flow). This exchange is an integral part of the global climate system, with important links and feedbacks generated through its influence on surface energy and moisture fluxes between continental water, atmosphere and oceans. Thus climate change and variability modify TWS. As briefly discussed earlier, human activities also directly affect TWS.

To estimate the contribution of TWS variations on sea level, we can simply consider the conservation of water mass in the Earth's system as in previous studies (e.g., Chen et al., 1998). On time scales of years to decades, solid Earth stores can be neglected, so that only changes in terrestrial reservoirs, ocean and atmosphere can be considered, with the mass conservation as follows:

$$\Delta M_{cont} + \Delta M_{ocean} + \Delta M_{atm} = 0 \tag{1}$$

where ΔM represents changes in water mass for the three reservoirs: continents, ocean and atmosphere.

Previous studies have shown that water vapour change in the atmosphere cannot be neglected at the annual time scale (Chen et al., 1998; Minster et al., 1999). On multidecadal time scale, it is generally considered that change in atmospheric water storage is negligible (Trenberth and Smith, 2005), even if because of global warming, an increase of atmospheric water vapour is expected. However, because of the water holding capacity of the atmosphere, even with higher temperature, this contribution is expected to be small as far as sea level change is concerned. Trenberth and Smith (2005) showed that, on interannual time scale, water vapour fluctuations are mostly associated with ENSO (El Nino-Southern Oscillation) events and lead to up to ~0.5×10^{15} kg variations of the mass of the atmosphere. When translated into sea level equivalent, this corresponds to sea level fluctuations at the mm level. This is not negligible considering the range of interannual fluctuations of the global mean sea level during ENSO events (of about 8 mm; see later). However in the present study, we choose to ignore the water vapour contribution.

Thus Eq. (1) becomes:

$$\Delta M_{ocean} \approx -\Delta M_{cont}. \tag{2}$$

ΔM_{ocean} represents the change with time in mass of the ocean due to total fresh water input from continents (i.e., land waters plus land ice melt). It can be further expressed in terms of equivalent sea level change by simply dividing the total continental water volume change by the mean surface of the oceans (assumed equal to 360×10^6 km^2) and changing its sign. In the following, we only consider the land water contribution because it is the purpose of the present study (keeping in mind that global land ice fluctuations may eventually slightly contribute to the sea level interannual signal). The associated ΔM_{cont} component may then be quantified in estimating the change in water storage on land (with $\Delta M_{cont} = \Delta TWS$).

At a river basin scale, temporal change in water storage TWS is related to precipitation P, evapotranspiration E and river runoff R through the water balance equation:

$$dTWS/dt = P - E - R \tag{3}$$

If P, E and R, or TWS were known globally, it would be possible to use these hydrological parameters to estimate the effect of land water storage on sea level. GRACE space gravimetry provides direct measurements of TWS while hydrological models solve Eq. (3) to estimate TWS.

3. Data used in this study

3.1. Sea level data

For periods 1 (2003–2009) and 2 (1993–2003) GMSL is derived from satellite altimetry (Topex/Poseidon, Jason-1 and Jason-2). Data from two different groups are considered (CLS — Collecte Localisation Satellites, update from Ablain et al., 2009 and NASA/GSFC — Goddard Space Flight Center, Beckley et al., 2010). While altimetry-based GMSL trends agree well whatever the data processing group, slight differences are noticed on interannual time scale, as we will see later.

The altimetry data are corrected for the standard geophysical and environmental corrections, including instrumental drifts and bias (see Ablain et al., 2009; Beckley et al., 2010 for details).

For period 3 (1955–1995), we considered global mean sea level (GMSL) time series computed by Jevrejeva et al. (2006) from tide gauge records. These authors used 1023 RLR (Revised Local Reference) tide gauge records (monthly data) from the Permanent Service for Mean Sea Level (PSMSL) (Woodworth and Player, 2003). However, they excluded data from Japan due to lack of information about vertical land motion during earthquake events, as well as data from the Baltic Sea because they may not be representative of the global ocean. This led to a total of about 800 stations usable for the global mean sea level reconstruction. The maximum number of tide gauges in a given year is 585. No inverted barometer correction was applied. Tide gauge records were corrected for glacial isostatic adjustment (GIA) of the solid Earth (Peltier, 2001). To overcome geographical bias (sampling issue of station locations) a "virtual station" method has been used. In this method, stations close to each other are weighted much less than isolated ones and uncertainties depend on how considered stations are locally representative of the estimated sea level. Global mean sea level (GMSL) data and their errors (Jevrejeva et al., 2006) are available from http://www.psmsl.org/products/reconstructions/jevrejevaetal2006.php.

3.2. Terrestrial water storage

3.2.1. The ISBA-TRIP global hydrological model

ISBA is a relatively simple land surface model (LSM) that uses the force-restore method to calculate the time variation of the surface energy and water budgets (Noilhan and Planton, 1989) including snow pack evolution based on a simple one-layer scheme (Douville et al., 1995). The soil hydrology is represented by three layers: a thin surface layer (1 cm) included in the rooting layer and a third layer to distinguish between the rooting depth and the total soil depth (Boone et al., 1999). An exponential profile of the saturated hydraulic conductivity with soil depth is also assumed for the soil column. This type of profile attempts to represent the fact that roots and organic matter favor the development of macropores and enhance water movement near the soil surface, and that soil compaction is an obstacle for vertical water transport in the deep soil (Decharme et al., 2006). The soil water content varies with surface infiltration, soil evaporation, plant transpiration and deep drainage. The infiltration rate is computed as the difference between the through-fall rate and the surface runoff. The through-fall rate is the sum of rainfall not intercepted by the canopy, dripping from the interception reservoir and snowmelt from the snow pack. ISBA also uses a comprehensive parameterization of sub-grid hydrology to account for the heterogeneity of precipitation, topography and vegetation within each grid cell (Decharme and Douville, 2006).

The total runoff integrating pathways (TRIP) was developed at Tokyo University by Oki and Sud (1998). It is a simple river routing model (RRM) used to convert the daily runoff simulated by ISBA into river discharge on a global river channel network here defined at 1° by 1° resolution. The runoff part of the simulated TWS can be validated using direct comparison between simulated and observed discharge. TRIP is a simple linear model based on a single prognostic equation for the water mass within each grid cell of the hydrologic network. In other words, TRIP only simulates a surface stream reservoir and the stream flow velocity is assumed constant and uniform at $0.5\ \mathrm{m\ s^{-1}}$.

The outputs of the ISBA-TRIP model cover the period January 1950 to December 2006, with values given at monthly interval on a 1°×1° grid. They are based on a run in forced mode. The global meteorological forcing was provided by the Princeton University (available online at http://hydrology.princeton.edu) on a 3-hourly time step and at a 1° resolution (see Alkama et al., 2010 for more details).

3.2.2. GRACE data

Raw GRACE data are processed by different groups belonging to the GRACE project (Center for Space Research —CSR, Jet Propulsion Laboratory —JPL— in the USA and Geo-ForschungsZentrum —GFZ— in Germany). GRACE data are also processed by other groups (GSFC/NASA in the USA; GRGS — Groupe de Recherche en Géodésie Spatiale — in France and DUT — Delft University of Technology— in The Netherlands). The GRACE products delivered over land by all groups are time series of equivalent water height, expressed either in terms of spherical harmonic expansion or as gridded data. Several GRACE product releases have been available from the GRACE project, each time with substantial improvement. Here we use different GRACE data sets: (1) the latest release (RL04) from the TELLUS website (http://grace.jpl.nasa.gov/data/mass/) for three solutions: the CSR, GFZ and JPL solutions (1°×1° global grids at monthly interval). The RL04 release includes an implementation of the carefully calibrated combination of destripping and smoothing, with a 300 km half-width Gaussian filter (Chambers, 2006). These GRACE products are also corrected for post-glacial rebound (the solid Earth response to last deglaciation, also sensed by GRACE) using the Paulson et al. (2007) model (but note that, as we focus here on interannual variability, we do not need to take care of this purely secular effect). These time series cover the period from August 2002 through July 2009. We also analysed GRGS solutions (updated from Biancale et al., 2007; data available at http://bgi.cnes.fr:8110/geoid-variations/). Processing of the GRGS GRACE data is described in detail in Bruinsma et al. (2010). The data consist of 10-day 1°×1° gridded solutions expressed in equivalent water height (their actual spatial resolution is about 400 km; Bruinsma et al., 2010). They cover the period from July 2002 to April 2009.

As in Llovel et al. (2010a), we computed water storage change over the 33 largest world river basins (see Fig. 1 for location). The river basin contours are based on masks of 1° resolution from Oki and Sud (1998). To estimate the water storage (i.e., water volume) contribution of individual river basins at each time step, the spatial average of GRACE equivalent water height has been computed over the area included inside the basin contour, then multiplied by the basin area. This analysis was repeated for each of the three CSR, GFZ and JPL GRACE products, from which an average TWS time series was deduced. Similar calculations were performed with the GRGS solutions.

4. Results

Each sea level and TWS time series has been detrended and the seasonal cycles (annual plus semi-annual) have been removed (12-month and a 6-month period sinusoids have been adjusted to each time series and removed). Each residual time series had its mean value set to zero over the time span of interest. TWS from both GRACE and ISBA-TRIP outputs was further expressed in terms of equivalent sea level (ESL) as explained in Section 2. In the following, this quantity is called TWS-ESL.

4.1. Period 1 (2003–2009)

For period 1 (2003–2009) GMSL is based on satellite altimetry data (updated from Ablain et al., 2009). For this time span, we have removed steric effects from the GMSL (i.e., the effects of ocean temperature and salinity) before comparing sea level variations with GRACE-based TWS-ESL. In effect, sea level variations result from both steric and mass effects. As we focus here on a mass component (the land water storage contribution), it is appropriate to remove the steric effects to observed global mean sea level. This is done using Argo profiling floats data processed by Guinehut et al. (2009). The steric sea level computation is described in another paper (Llovel et al., 2010b). Fig. 2 compares interannual variability in GMSL (corrected for steric effects) and TWS-ESL from GRACE (sum of the 33 river basin contributions). The two GRACE time series are shown (i.e., the mean CSR/GFZ/JPL solution and the GRGS solution). Fig. 2

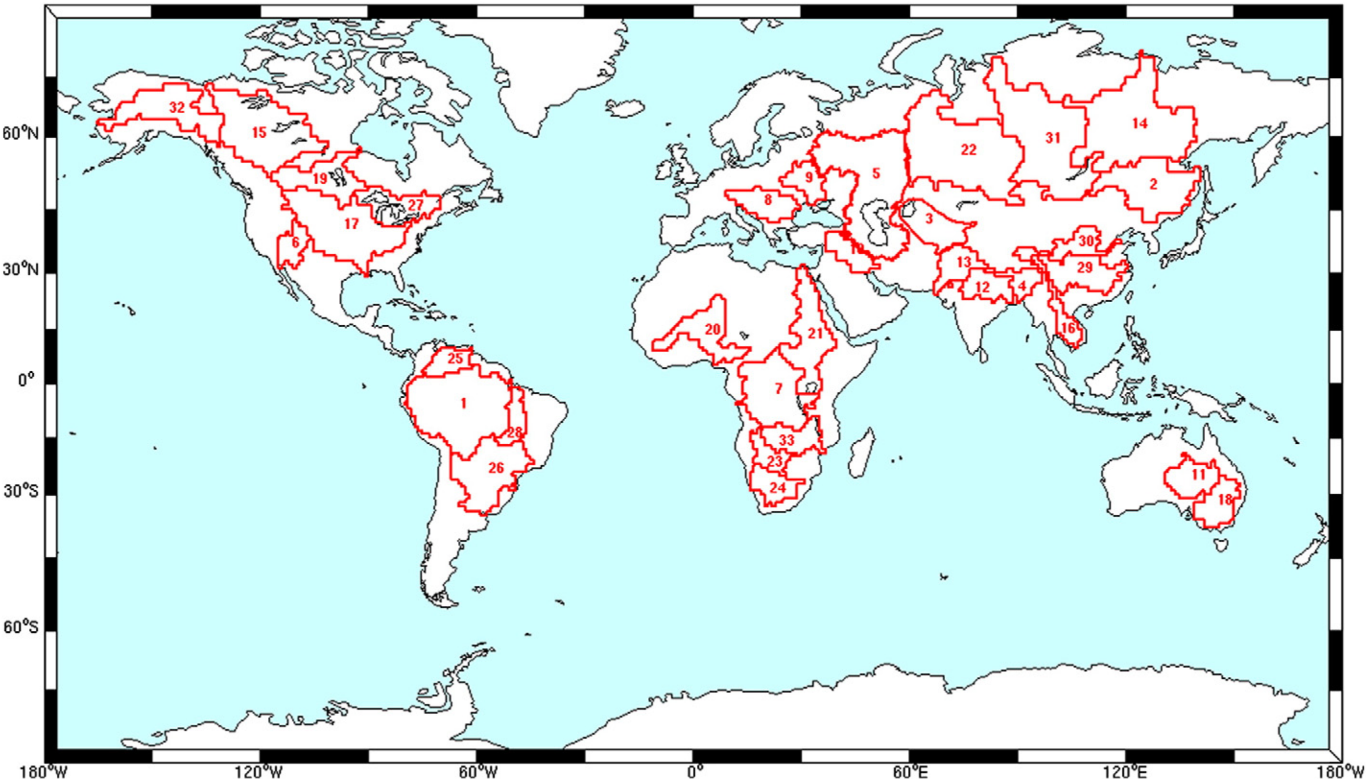

Fig. 1. Location of the 33 river basins used for computing TWS from GRACE and ISBA-TRIP data. List of the 33 river basins considered and associated number: 1: Amazon, 2: Amur, 3: Aral, 4: Brahmaputra, 5: Caspienne/Volga, 6: Colorado, 7: Congo, 8: Danube, 9: Dniepr, 10: Euphrates, 11: Eyre, 12: Ganges, 13: Indus, 14: Lena, 15: Mackenzie, 16: Mekong, 17: Mississippi, 18: Murray, 19: Nelson, 20: Niger, 21: Nile, 22: Ob, 23: Okavango, 24: Orange, 25: Orinoco, 26: Parana, 27: St-Lawrence, 28: Tocantins, 29: Yangtze, 30: Yellow, 31: Yenisey, 32: Yukon, and 33: Zambeze.

also shows TWS-ESL from the ISBA-TRIP model (same 33 river basins). As mentioned previously, all time series are detrended and seasonal signal has been removed. A 3-month running mean smoothing was applied to the data.

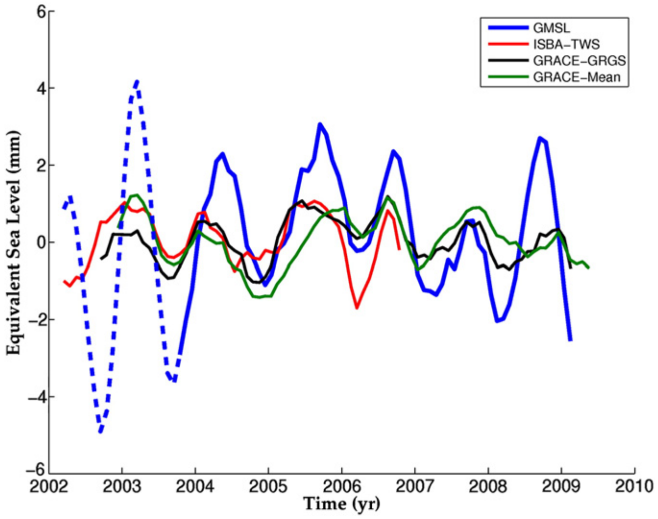

Fig. 2. Interannual variability of the altimetry-based global mean sea level (GMSL) corrected for thermal expansion over 2003–2009 (blue curve —data from Llovel et al., 2010b) and terrestrial water storage (expressed in equivalent sea level) —TWS-ESL from the ISBA-TRIP model (red curve) and GRACE (green curve: data from the mean CSR/GFZ/JPL; black curve: data from GRGS updated from Llovel et al., 2010a). The time series are detrended, and the seasonal cycle is removed. The time series are smoothed with a 3-month window.

Looking at Fig. 2, we first note that the two GRACE solutions agree reasonably well (correlation coefficient of 0.61 at the 95% confidence level). They also agree well with ISBA-TRIP TWS-ESL over their overlapping time span. Interannual fluctuations in GMSL (corrected for steric effects) are positively correlated with TWS-ESL (correlation coefficient of 0.5 and 0.7 with the mean CSR/GFZ/JPL and GRGS solutions respectively at the 95% confidence level). We note that the agreement between sea level and TWS improves beyond 2004. As discussed in Llovel et al. (2010b), the poor Argo coverage in 2002–2003 underestimates the steric sea level correction. For that reason, the corrected sea level for 2002–2003 is shown by a dashed curve. However, the overall agreement over the 2003–2009 time span is good. This result suggests that for the recent years, interannual variability of GMSL is, at least partly, caused by year-to-year variability of land water storage. Fig. 2 is suggestive of nearly annual fluctuations. However, as already mentioned, the annual cycle has been removed. A spectral analysis –not shown– of the three TWS-ESL time series (i.e., the two GRACE solutions and the ISBA-TRIP outputs, with data at monthly interval) displays peaks in the 14–16 month and 24–25 month wavebands. The origin of these signals is unclear and needs further investigation.

Following the conclusions of Ngo-Duc et al. (2005b), we investigated whether the tropical river basins mostly contribute to the TWS interannual variability. For that purpose, we constructed the GRACE-based TWS time series (data from GRGS only), considering only the following basins: Amazon, Orinoco, Niger, Congo, Okavango, Indus, Ganges and Mekong. The corresponding curve, expressed in water volume is shown in Fig. 3. For comparison the curve for the 33 basins is superimposed. Fig. 3 clearly shows the dominant contribution of the tropical river basins. On Fig. 3 we also show the Amazon contribution. Interestingly, the Amazon basin alone is a major contribution to the total signal. Thus we conclude that interannual variability in sea level is highly associated with water fluctuations of the Amazon basin.

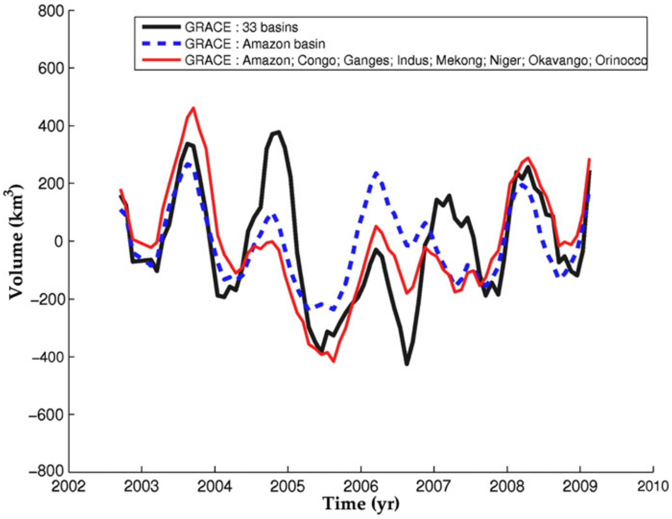

Fig. 3. TWS variability (data from GRGS) over 2003–2009: total (33 river basins; black curve); contribution from 8 tropical river basins (red curve: 1: Amazon, 7: Congo, 12: Ganges, 13: Indus, 16: Mekong, 20: Niger, 23: Okavango, and 25: Orinoco) and contribution from the Amazon only (blue curve). The time series are detrended, and the seasonal cycle is removed. The time series are smoothed with a 3-month window.

4.2. Period 2 (1993–2003)

For this time span (1993–2003), we compared TWS-ESL from ISBA-TRIP with the altimetry-based global mean sea level. Here we show two altimetry-based GMSL curves (from Ablain et al., 2009 —called CLS, and from Beckley et al., 2010 —called GSFC). A 3-month running mean smoothing was applied to the data. The CLS (Fig. 4a) and GSFC (Fig. 4b) sea level curves, superimposed to ISBA-TRIP TWS-ESL, are presented separately for clarity. As for period 1, the two quantities can be directly compared. However, unlike for period 1, we did not correct for steric effects here. For the pre-Argo period, steric effects are mostly based on XbT temperature data, subjects to significant uncertainties. A recent study by Lyman et al. (2010) compares different global ocean heat content curves computed by different teams for the period 1993–2008 and shows large difference in interannual variability, especially for the pre-Argo years (before 2002), revealing large uncertainties introduced by the XbT measurements (in particular the XbT depth bias correction). As global heat content and thermal expansion follow similar time evolution, we choose to not correct sea level for steric effects, in order not to introduce spurious noise on interannual time scale.

Fig. 4a,b shows significant correlation (~0.5 and ~0.7 with CLS and GSFC products respectively at the 95% confidence level) between altimetry-based sea level and TWS-ESL (from ISBA-TRIP), especially during the 1997–1998 ENSO event, and also between 2002 and 2004 (another ENSO period). During such events, positive sea level anomalies seem to essentially result from land water storage change (more specifically, from water deficit on land). The study by Ngo-Duc et al. (2005b) analysed the cause for a higher/smaller than normal annual cycle in GMSL (based on Topex/Poseidon altimetry) in 1997–1998, during the large 1997–1998 ENSO event. Using the Orchidee LSM, run in a coupled mode with the Atmospheric General Circulation Model of the Laboratoire de Meteorologie Dynamique, they showed that higher/smaller annual amplitude in sea level (corrected for thermal expansion) in 1997/1998 could be explained by higher/smaller TWS-ESL, as a result of particularly dry conditions on land due to important precipitation deficit over tropical land (inside the 20°N–20°S domain) during this ENSO event. Year-to-year fluctuations in TWS annual amplitude translate into interannual variability. This is exactly what Fig. 4a,b shows during the 1997–1998 ENSO. Previous results based on the Orchidee LSM are indeed confirmed when using the ISBA-TRIP model. Thus, we can quantitatively explain GMSL anomaly in 1997–1998 by a net water deficit on land during this ENSO event. The good correspondence seen between GMSL and TWS-ESL around 2002–2004 (another ENSO period) suggests that the same hydrological conditions produce similar effects.

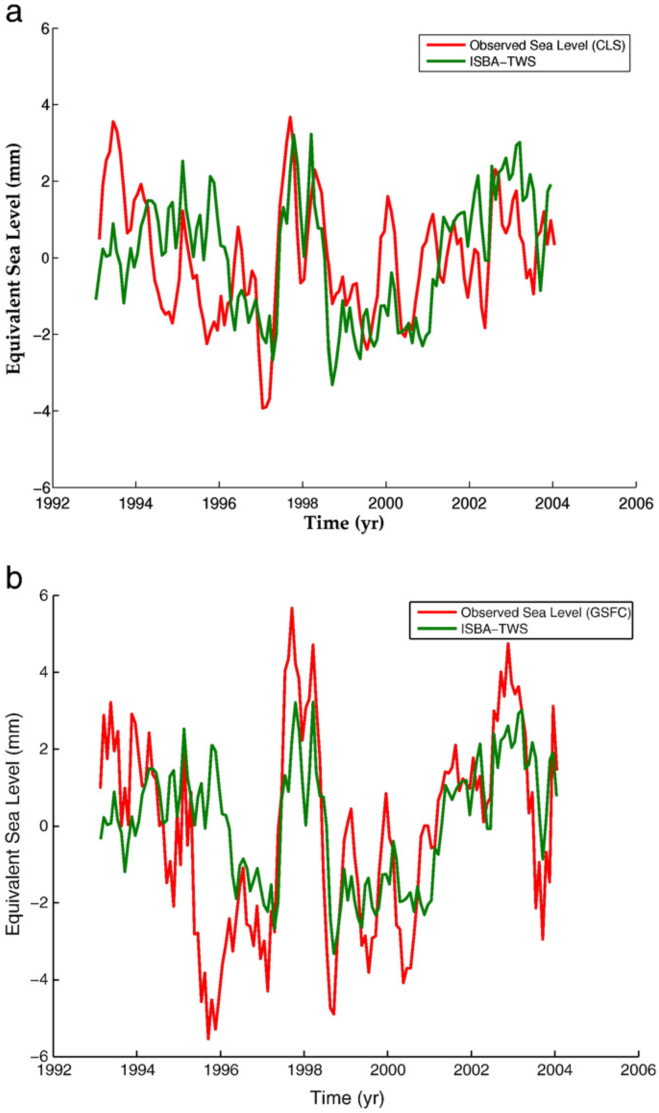

Fig. 4. Interannual variability of the altimetry-based global mean sea level (solid curve) and terrestrial water storage (expressed in equivalent sea level) —TWS-ESL from the ISBA-TRIP model (dashed curve) over 1993–2003. (a) Global mean sea level from Ablain et al. (2009) — CLS; (b) global mean sea level from Beckley et al. (2010) —GSFC. The time series are detrended, and the seasonal cycle is removed. The time series are smoothed with a 3-month window.

In Fig. 4a,b, we note some discrepancy between sea level and TWS-ESL in 1995. We cannot exclude a steric origin (as steric effects are not corrected for). However, the two sea level curves do not perfectly coincide at this epoch, suggesting that some efforts should be made to better estimate interannual variability in global mean sea level. Besides, these disagreements could be due to some other phenomena not considered or modelled in the ISBA-TRIP model.

4.3. Period 3 (1955–1995)

Fig. 5 shows the interannual to decadal variability in sea level (based on tide gauge data from Jevrejeva et al., 2006) and TWS-ESL (from ISBA-TRIP) between 1955 and 1995. Here the two curves have

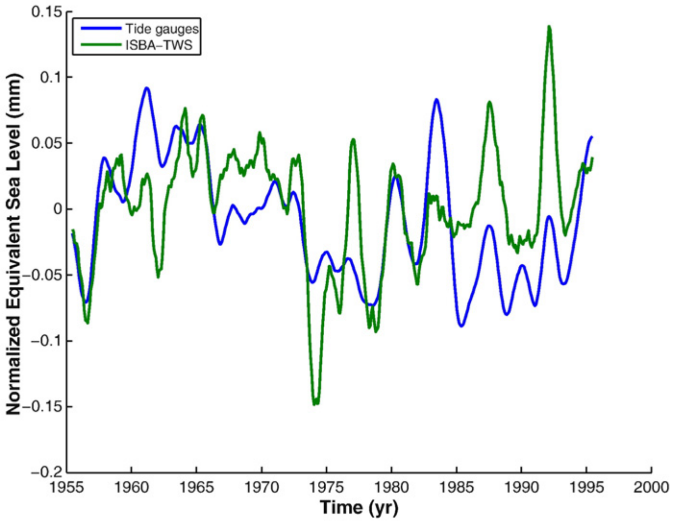

Fig. 5. Interannual variability of the global mean sea level (solid curve; data from Jevrejeva et al., 2006) and terrestrial water storage (expressed in equivalent sea level) —TWS-ESL from the ISBA-TRIP model (dashed curve)— between 1955 and 1995. The time series are detrended, and the seasonal cycle is removed. The time series are smoothed with an 11-month window.

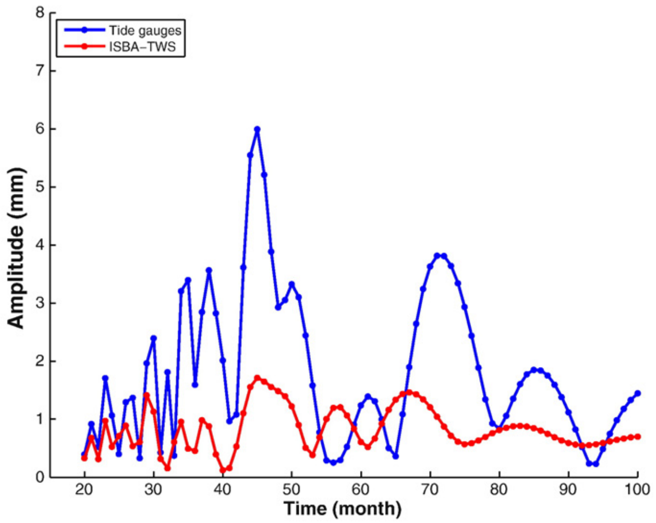

Fig. 6. Amplitude spectra of the data shown in Fig. 5 (sea level data: solid curve; TWS-ESL: dashed curve).

been normalized (norm defined by the largest singular value of the time series). In effect, as shown in Prandi et al. (2009), coastal mean sea level displays higher interannual variability than GMSL based on global data coverage (e.g. from satellite altimetry). This is a sampling effect due to sparse tide gauge records when compared to the 'true' global mean computed with quasi global altimetry data. For comparing with TWS-ESL (which represents a global signal), we thus decided to normalize both time series to not artificially enhance the observed coastal sea level variability. As for period 2, steric effects have not been corrected for. An 11-month running mean smoothing has been applied to the data. From Fig. 5, we note that the two curves are positively correlated (correlation of ~0.5 at the 95% confidence level). The fluctuations are suggestive of ENSO (El Nino-Southern Oscillation)-type variability (as observed in 1997–1998 during period 2). For example, we note positive sea level and TWS-ESL anomalies in 1982–1983 and 1986–1987, periods of strong ENSO events. We performed a spectral analysis (based on data at monthly interval) of mean sea level and TWS-ESL (note that in this case mean sea level and TWS-ESL are not normalized). Amplitude spectra are shown in Fig. 6. Dominant peaks in sea level and TWS-ESL are seen around 3–4 years 6–7 years, as expected for a dominant ENSO forcing. Previous studies (e.g., Merrifield et al., 2009; Nerem et al., 2010) have reported high correlation between detrended global mean sea level (over the altimetry period) and ENSO proxies, in particular the Multivariate ENSO Index —MEI (MEI is computed with the six main observed variables over the tropical Pacific which are sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky, for more information see Wolter, 1987). Nerem et al. (2010) suggest that the observed correlation could result from either a change in ocean heat content associated with ENSO or a change in land/ocean precipitation patterns during ENSO. Our analysis of TWS suggests that it is rather the second process that leads to the observed correlation, more specifically the change in land water storage during ENSO events.

5. Discussion

The results presented earlier for three different time frames (2003–2009, 1993–2003 and 1955–1995) reveal the important contribution of global terrestrial water storage variations to the interannual variability of the global mean sea level. For periods 2 (1993–2003) and 3 (1955–1995) the results are based on the ISBA-TRIP model. Furthermore, for period 1 (2003–2009) we used GRACE space gravimetry data. This study reports a dominant ENSO signature in interannual GMSL and TWS fluctuations. Quantitative comparison with global terrestrial water storage variations shows that the process involved is water exchange between land river basins and oceans, with drier than normal land during ENSO events. As suggested by Ngo-Duc et al. (2005b), tropical basins are probably the regions mostly involved in this exchange. The Amazon basin in particular shows a dominant contribution (at least for period 1) in the exchange of water between land and oceans on interannual time scale. This study points towards a significant influence of the terrestrial water cycle on sea level. It provides an explanation of processes involved in the correlation reported by Nerem et al. (2010) between GMSL and ENSO proxies. It also provides a quantitative explanation of the origin of the interannual variability in sea level. This interannual variability in sea level has been noticed in many previous studies, but so far had remained unexplained. Besides, another potential contribution remains to be investigated: the atmospheric water vapour reservoir. Variability of water vapour may eventually explain part of the difference between global mean sea level and land water storage at interannual time scale.

Acknowledgements

W. Llovel is supported by a PhD Grant from CNRS and the Region Midi-Pyrenees. M. Becker and R. Alkama are supported by Post Doctoral fellowships from the ANR project 'CECILE' and the RTRA-STAE project 'CYMENT'. We thank R.S. Nerem and two anonymous reviewers for very useful comments. GRACE data of the TELLUS website were processed by D. P. Chambers, supported by the NASA Earth Science REASoN GRACE Project, and are available at http://grace.jpl.nasa.gov.

References

Ablain, M., Cazenave, A., Guinehut, S., Valladeau, G., 2009. A new assessment of global mean sea level from altimeters highlights a reduction of global slope from 2005 to 2008 in agreement with in-situ measurements. Ocean Sci. 5 (2), 193–201.

Alkama, R., Decharme, B., Douville, H., Voldoire, A., Tyteca, S., Le Moigne, P., Becker, M., Cazenave, A., Sheffield, J., 2010. Global evaluation of the ISBA-TRIP continental hydrological system. Part 1: comparison to GRACE terrestrial water storage estimates and in-situ river discharges. J. Hydromet. 583–600. doi:10.1175/2010JHM1211.1.

Beckley, B.D., Zelensky, N.P., Holmes, S.A., Lemoine, F.G., Ray, R.D., Mitchum, G.T., Desai, S., Brown, S.T., 2010. Assessment of the Jason-2 extension to the TOPEX/Poseidon, Jason-1 sea surface height time series for global mean sea level monitoring. Mar. Geodesy 33 (1), 447–471.

Biancale, R., Lemoine, J.-M., Balmino, G., Loyer, S., Bruisma, S., Perosanz, F., Marty, J.-C., Gégout, P., 2007. 3 Years of Geoid Variations from GRACE and LAGEOS Data at 10-day Intervals from July 2002 to March 2005, CNES/GRGS Product. data available on CD-ROM, also on BGI web page: http://bgi.cnes.fr/.

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L., Unnikrishnan, A., 2007. Observations: oceanic climate and sea level. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergouvernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, USA.

Boone, A., Calvet, J.-C., Noilhan, J., 1999. Inclusion of a third soil layer in a land-surface scheme using the force-restore method. J. Appl. Meteorol. 38, 1611–1630.

Bruinsma, S., Lemoine, J.M., Biancale, R., Vales, N., 2010. CNES/GRGS 10-day gravity field models (release 2) and their evaluation. Adv. Space Res. 45 (4), 587–601. doi:10.1016/j.asr.2009.10.012.

Cazenave, A., Llovel, W., 2010. Contemporary sea level rise. Annu. Rev. Mar. Sci. 2, 145–173.

Chambers, D.P., 2006. Evaluation of new GRACE time-variable gravity data over the ocean. Geophys. Res. Lett. 33 (17), LI7603.

Chao, B.F., 1995. Anthropogenic impact on global geodynamics due to reservoir water impoundment. Geophys. Res. Lett. 22, 3529–3532.

Chao, B.F., Wu, Y.H., Li, Y.S., 2008. Impact of artificial reservoir water impoundment on global sea level. Science 320 (5873), 212–214.

Chen, J.L., et al., 1998. Seasonal global water mass budget and mean sea level variations. Geophys. Res. Lett. 25, 3555–3558.

Decharme, B., Douville, H., 2006. Introduction of a sub-grid hydrology in the ISBA land surface model. Climate Dyn. 26, 65–78.

Decharme, B., Douville, H., Boone, A., Habets, F., Noilhan, J., 2006. Impact of an exponential profile of saturated hydraulic conductivity within the ISBA LSM: simulations over the Rhône Basin. J. Hydromet. 7, 61–80.

Douville, H., Royer, J.-F., Mahfouf, J.-F., 1995. A new snow parameterization for the Météo-France climate model. Part 1: validation in stand-alone experiments. Climate Dyn. 12, 21–35.

Gornitz, V., 2001. Impoundment, groundwater mining, and other hydrologic transformations: impacts on global sea level rise. In: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), Sea Level Rise, History and Consequences. Academic Press, San Diego, California, pp. 97–119.

Guinehut, S., Coatanoan, C., Dhomps, A.L., Le Traon, P.Y., Larnicol, G., 2009. On the use of satellite altimeter data in Argo quality control. J. Atmos. Oceanic Technol. 26, 395–402.

Jevrejeva, S., Grinsted, A., Moore, J.C., Holgate, S., 2006. Nonlinear trends and multiyear cycles in sea level records. J. Geophys. Res. 111, C09012. doi:10.1029/2005JC003229.

Llovel, W., Becker, M., Cazenave, A., Crétaux, J.F., 2010a. Contribution of land water storage change to global mean sea level from GRACE and satellite altimetry. C.R. Geosci. 342, 179–188.

Llovel, W., Guinehut, S., Cazenave, A., 2010b. Regional and interannual variability in sea level over 2002–2009 based on satellite altimetry, Argo float data and GRACE ocean mass. Ocean Dyn. 60, 1193–1204. doi:10.1007/s10236-010-0324.

Lyman, J., Good, S.A., Gouretski, V.V., Ishii, M., Johnson, G.C., Palmer, M.D., Smith, D.M., Willis, J.K., 2010. Robust warming of the global upper ocean. Nature 465, 334–337.

Merrifield, M., Nerem, R.S., Mitchum, G.T., Miller, L., Leuliette, E., Gill, S., Woodworth, P.L., 2009. Sea level variations, 2008 annual assessment [in “State of the Climate in 2008”]. Bull. Am. Meteorol. Soc. 90 (8), S62–S196.

Milly, P.C.D., Cazenave, A., Gennero, M.C., 2003. Contribution of climate-driven change in continental water storage to recent sea-level rise. Proc. Natl Acad. Sci. 100, 13158–13161. doi:10.1073/pnas.2134014100.

Milly, P.C.D., Cazenave, A., Famiglietti, J., Gornitz, V., Laval, K., Lettenmaier, D., Sahagian, D., Wahr, J., Wilson, C., 2010. Terrestrial water storage contributions to sea level rise and variability. In: Church, J., Woodworth, P., Aarup, T., Wilson, S., et al. (Eds.), Proceedings of the WCRP Workshop ‘Understanding sea level rise and variability’. Blackwell Publishing, Inc.

Minster, J.F., Cazenave, A., Serafini, Y.V., Mercier, F., Gennero, M.C., Rogel, P., 1999. Annual cycle in mean sea level from Topex-Poseidon and ERS-1: inferences on the global hydrological cycle. Glob. Planet. Change 20, 57–66.

Nerem, R.S., Chambers, D.P., Choe, C., Mitchum, G.T., 2010. Estimating mean sea level change from the TOPEX and Jason altimeter missions. Mar. Geodesy 33 (1), 435–446.

Ngo-Duc, T., Laval, K., Polcher, J., Lombard, A., Cazenave, A., 2005a. Effects of land water storage on global mean sea level ofer the past 50 years. Geophys. Res. Lett. 32, L09704. doi:10.1029/2005GL022719.

Ngo-Duc, T., Laval, K., Polcher, Y., Cazenave, A., 2005b. Analyses of the contribution of continental water to sea level variations during the 1997–1998 ENSO event; comparison between the AMIP simulations and the Topex/Poseidon satellite data. J. Geophys. Res. 110, DO9103. doi:10.1029/2004JD004940.

Noilhan, J., Planton, S., 1989. A simple parameterization of land surface processes for meteorological models. Mon. Weather Rev. 117, 536–549.

Oki, T., Sud, Y.C., 1998. Design of Total Runoff Integrating Pathways (TRIP)— a global river channel network. Earth Interact. 2 (1), 1–37.

Paulson, A., Zhong, S., Wahr, J., 2007. Inference of mantle viscosity from GRACE and relative sea level data. Geophys. J. Int. 171, 497–508.

Peltier, W.R., 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), Sea Level Rise. Elsevier, New York.

Prandi, P., Cazenave, A., Becker, M., 2009. Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007. Geophys. Res. Lett. 36. doi:10.1029/2008GL036564, 2009.

Ramillien, R., Bouhours, S., Lombard, A., Cazenave, A., Flechtner, F., Schmidt, R., 2008. Land water contributions from GRACE to sea level rise over 2002–2006. Glob. Planet. Change 60, 381–392.

Sahagian, D., 2000. Global physical effects of anthropogenic hydrological alterations: sea level and water redistribution. Glob. Planet. Change 25, 39–48.

Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F., Watkins, M.M., 2004. GRACE measurements of mass variability in the Earth system. Science 305, 503–505.

Trenberth, K.E., Smith, L., 2005. The mass of the atmosphere: a constraint on global analyses. J. Climate 18, 864–875.

Vörösmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., Lough, J.A., 1997. The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26, 210–219.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37, L20402. doi:10.1029/2010GL044571.

Wahr, J., Swenson, S., Zlotnicki, V., Velicogna, I., 2004. Time-variable gravity from GRACE: first results. Geophys. Res. Lett. 31, L11501. doi:10.1029/2004GL019779.

Wolter, K., 1987. The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. J. Climate Appl. Meteorol. 26, 540–558.

Woodworth, P.L., Player, R., 2003. The permanent service for mean sea level: an update to the 21st century. J. Coast. Res. 19, 287–295.